UN-TAPPING ECONOMIC AND CLIMATE CHANGE IMPACT OF REGENERATIVE AGRICULTURE IN INDIA: OPPORTUNITY AND APPROACH

A Thesis Submitted to

Institute of Advanced Research
Koba Institutional Area
Gandhinagar-382426
Gujarat, India

For the Award of the Degree

Doctor of Philosophy

in

BUSINESS AND MANAGEMENT

Submitted by

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(JANUARY-2025)

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GENERAL OVERVIEW

Regenerative agriculture, focuses on restoring soil health, enhancing biodiversity, and sequestering carbon, offers a way to address climate change while potentially driving economic benefits. By examining its impact on GDP, the thesis provides insights into how transitioning to regenerative practices contributes to long-term economic resilience, especially in agricultural-based economies. The research highlights the economic viability of sustainable farming, analysing its potential to create local employment, stimulate rural development, and reduce environmental costs.

This study addresses these gaps by integrating water use efficiency (WUE) into the broader context of regenerative agriculture, recognizing it as a critical driver for both sustainable farming practices and economic productivity. By examining the direct link between regenerative practices and GDP growth, we provide empirical evidence of the economic benefits of improved WUE, filling the gap in research that has traditionally overlooked this connection. The use of robust analytical models, such as Simultaneous Equations Models (SEM), allows for a more comprehensive understanding of the long-term economic impacts of regenerative agriculture, including its effect on macroeconomic indicators. Furthermore, this study bridges the fragmented understanding of resource efficiency by exploring how WUE interacts with other regenerative practices to optimize overall resource use and productivity. Additionally, we focus on the role of regenerative agriculture in climate change adaptation, highlighting how WUE contributes to reducing water stress and mitigating greenhouse gas emissions, thus addressing the inadequate climate change insights found in earlier research.

The aim of this paper is to explore the impact of water use efficiency (WUE) on regenerative agriculture practices and its contribution to the economic development of India. It seeks to identify the critical determinants of WUE in Indian agriculture, examining factors that influence water management in farming systems.

The paper also aims to analyse the impact of changes in WUE on soil nutrient balance and crop yields, exploring how improvements in water management can enhance soil health and productivity. Additionally, the research investigates how fertilizer use mediates the relationship between WUE and agricultural productivity, assessing how optimal fertilizer application can complement efficient water use for higher yields. Finally, the paper explores the impact of WUE on carbon emissions from agricultural activities, aiming to understand how water efficiency can contribute to reducing the carbon footprint of farming practices.

The research deepens the fields of agronomy and environmental economics and raises public awareness about the economic advantages of adopting regenerative practices, fostering wider acceptance and implementation across the agricultural sector. In this study, we employ a Simultaneous Equations Model (SEM) to examine the role of water use efficiency (WUE) in promoting regenerative agriculture and enhancing India's economy. SEM is used to analyse the interrelationships between key variables such as WUE, crop yields, GDP per capita, employment, and environmental sustainability. To ensure robust results, statistical procedures like correlation analysis, multicollinearity checks, and model fitting are applied.

In conclusion, improving water use efficiency (WUE) through regenerative agriculture has significant potential to contribute to GDP growth by enhancing agricultural productivity and sustainability. It can also stimulate rural employment and development by creating job opportunities in water management, sustainable farming practices, and related industries. Additionally, increased WUE can open up export and trade opportunities by making agricultural products more competitive in global markets.

Objectives of the study

1. To evaluate the impact of water use efficiency on the sustainability of regenerative agriculture, with a specific focus on soil health and carbon sequestration, and to assess its subsequent effects on the country’s gross domestic product (GDP), value added in agriculture, population, and employment.
2. To identify, analyze, and evaluate the key environmental (e.g., emissions from agricultural land, crop residue burning), agricultural (e.g., crop production data, agricultural land area), and economic (e.g., GDP, value added in agriculture, population and employment in agriculture) factors affecting water use efficiency in Indian agriculture.
3. To investigate the relationship between changes in water use efficiency, soil nutrient balance (nutrient inputs such as atmospheric deposition, biological fixation, manure, mineral fertilizers, and seed versus nutrient outputs such as crop removal, leaching, and volatilization), and crop yields (crop area and production) to optimize agricultural productivity and sustainability.

4. To analyze the role of fertilizer application (e.g., cropland nitrogen) in shaping the relationship between water use efficiency and agricultural productivity (crop area and production) for sustainable and productive farming systems.
5. To evaluate how improvements in water use efficiency influence carbon emissions from agriculture (e.g., emissions from agricultural land, crop residue burning) to develop strategies for reducing the carbon footprint of agricultural practices.

PRESENT INVESTIGATION

Regenerative practices can increase the number of mixed farming systems in this area by integrating and stacking farm income while simultaneously rejuvenating eroded and potentially nutrient-deficient soils to increase productivity. Over time, the anticipated result of these practices is the emergence of natural drought-resistant traits within Indian farming systems.

The main research question is: What are the economic implications for possible future regenerative agriculture management practices in India? A proposed result of the long-term implementation of regenerative agriculture management practices is the formation of agricultural practices. Empirically, this could be achieved on a farm level by reducing the need for artificial fertilizers, thus creating room for increased whole-farm profitability. This study is country-specific and related to the ongoing soil regenerative agriculture management practices trial, which could help farmers assess the economic profitability of integrating regenerative management practices into their current farming systems.

This study employs a quantitative research approach to investigate the role of water use efficiency (WUE) in advancing regenerative agriculture and driving economic development in India. The rationale for using a quantitative approach includes several key factors:

1. **Objective Measurement:** Quantitative research allows for precise, objective measurements of variables like WUE, crop yields, soil nutrient balance, and economic outcomes. These measurements enable reliable statistical analysis.
2. **Large-Scale Data Analysis**: This study utilizes extensive data from the FAOSTAT and other relevant databases, which provide comprehensive quantitative data on agriculture, water use, and economic indicators, such as Gross Domestic Product (GDP), employment, and emissions. A quantitative approach is essential to effectively analyze such large-scale datasets.

3. **Statistical Modelling**: A Simultaneous Equations Model (SEM) is employed to investigate complex interrelationships among variables such as WUE, soil nutrient balance, crop yields, and economic indicators. SEM necessitates advanced statistical techniques, making a quantitative approach appropriate for capturing these interactions.
4. **Generalizability**: The findings of this study, derived from statistically analyzing large datasets, can be generalized to broader agricultural contexts in India. The quantitative methods employed ensure the results are applicable on a national scale, especially for policy recommendations.
5. **Hypothesis Testing**: The study aims to test specific hypotheses related to WUE's influence on agricultural productivity, soil nutrient management, economic growth, and environmental sustainability. The quantitative approach is well-suited for hypothesis testing, enabling conclusions based on empirical evidence.

Specific components of the quantitative approach

1. **Data Collection**: Data were sourced from FAOSTAT and other relevant databases, focusing on key variables like Gross Domestic Product (GDP), agricultural production, employment, agricultural land use, soil nutrient balance, emissions on agricultural land, and water management variables such as Water Use Efficiency (WUE) and agricultural water withdrawal.
2. **Variable Analysis**: The study examines various quantitative variables, such as WUE, soil nutrient balance, crop yields, GDP per capita, and employment. These variables are analysed to understand their impact on agricultural productivity and sustainability.
3. **Simultaneous Equations Model (SEM):** The SEM is employed to analyze the interrelationships between key variables, such as WUE, soil nutrient balance, crop yields, and economic outcomes. This model is vital for understanding how improvements in water use efficiency can affect agriculture and economic development.
4. **Statistical Tools and Software:** The analysis is performed using R statistical software, which enables the handling of large datasets and the application of complex statistical methods, including correlation analysis, multicollinearity checks, and model diagnostics.

CHAPTER 1- INTRODUCTION AND OVERVIEW

Regenerative Agriculture primarily focuses on enhancing soil health, particularly by increasing soil organic matter (SOM), which improves soil fertility and resilience. This approach aims to mitigate climate change through carbon sequestration in soils. The effectiveness of increasing SOM varies depending on soil type and initial conditions, with greater potential seen in low-yielding regions where biomass input can significantly boost organic matter levels. Agroforestry, a key practice within Regenerative Agriculture, shows promise in sequestering carbon both above and below ground.

However, challenges persist, especially regarding nutrient management. While SOM enhances nutrient availability, global agriculture heavily relies on external inputs like mineral fertilizers to sustain yields. Practices that exclude these inputs risk soil degradation and reduced productivity over time, highlighting the delicate balance required in soil nutrient management.

Moreover, Regenerative Agriculture's impact on biodiversity, though central to its principles, often overlooks integrated pest management (IPM) and integrated weed control (IWM) strategies. These approaches, crucial for reducing chemical use and enhancing on-farm biodiversity, require extensive knowledge and monitoring but are essential for sustainable agricultural intensification.

In summary, while Regenerative Agriculture holds promise for carbon sequestration and biodiversity conservation, its success depends on effectively managing soil health, nutrient cycles, and integrating biodiversity-friendly practices across agricultural landscapes.

The divide between regenerative agriculture and climate- smart agriculture regenerative agriculture

Soil-based carbon storage strategies involve the reform of conventional farming practices globally, converting practices that degrade soil to a wide spectrum of alternative practices that regenerate its natural vigour and microbial capacity to sequester atmospheric elements, notably carbon and nitrogen. The research agency most clearly defining and working within the Regenerative Agriculture Paradigm is the Consultative Group for International Agricultural Research (CGIAR) and its program on Climate Change, Agriculture, and Food Security (CCAFS), which attempts to consolidate global data surrounding agroecological practices. The Regenerative Agriculture BMPs (Best Management Practices) are based on principles of agroecology. Their goal is to maintain viable farming systems by eliminating manufactured

inputs and solely utilizing ecosystem processes, such as cover cropping, manure-based fertilizer use, crop rotation, and integrated grazing.

Years of analysis of the complexity of soil ecosystems have allowed the scientific community to understand that microbial communities form the basis of highly fertile and carbon-rich soils. Evidence shows that it is possible for healthy microbial communities to produce sufficient nutrients for high crop yields, as well as promote biodiversity on farmland, which acts as a natural pest control system. Tillage—any form of ploughing or disrupting the soil—demonstrably leads to the oxidation of soils, damage to mycorrhizal fungi networks, and ultimately to the loss of organic carbon, and therefore of fertility. The use of GMOs or chemical inputs of any kind is not consistent with the goals of maintaining and enhancing soils' capacities to sustain the food system in the long term. As it requires a transition to no-till systems and an elimination of chemical inputs, the implementation of the Regenerative Agriculture paradigm throughout regions and corporate supply chains would require a holistic restructuring of the way societies produce food. This process has begun with developing sets of practices that need to be customized for each specific context in the broad spectrum of farming ecosystems. The adoption of a regenerative approach is stimulated by a recognition of input costs that could be saved by restoring ecosystem fertilization and irrigation processes (Anne-Marie Codur and Josephine Watson, 2018).

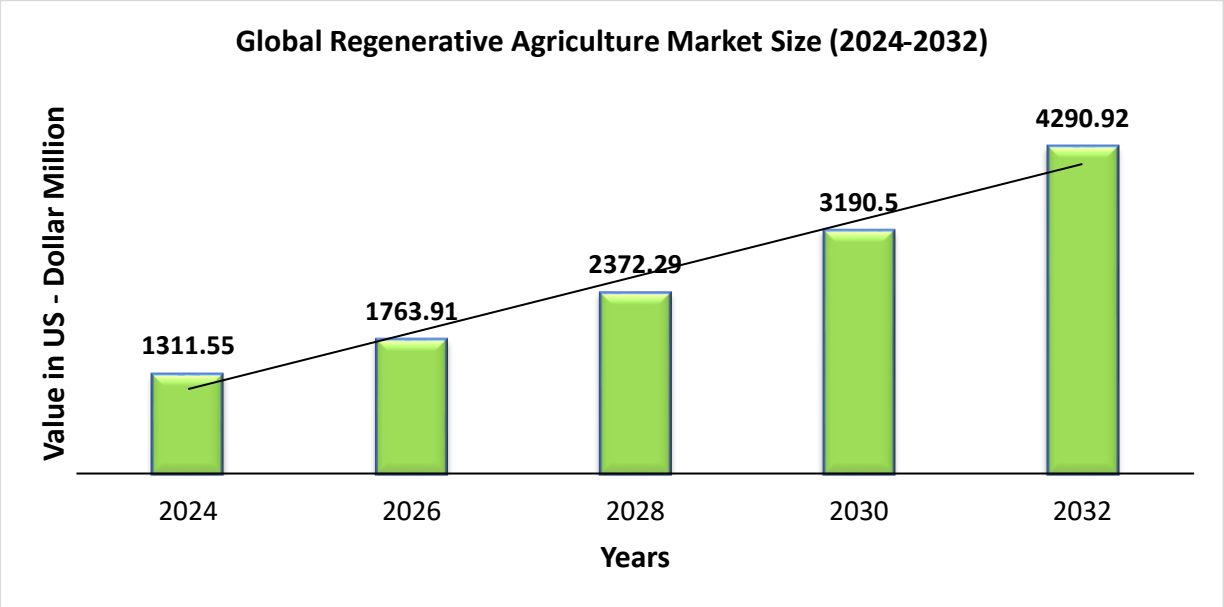
Principles	**Practices**
Minimize tillage	Zero-till, reduced tillage, conservation agriculture, controlled traffic
Maintain soil cover	Mulch, cover crops, permaculture
Build soil C	Biochar, compost, green manures, animal manures
Sequester carbon	Agroforestry, silvopasture, tree crops
Relying more on biological nutrient cycles	Animal manures, compost, compost tea, green manures and cover crops, maintain living roots in soil, inoculation of soils and composts, reduce reliance on mineral fertilizers, organic agriculture, permaculture
Foster plant diversity	Diverse crop rotations, multi-species cover crops, agroforestry
Integrate livestock	Rotational grazing, holistic (Savory) grazing, pasture cropping, silvopasture

Source: McGuire (2018), Burgess et al. (2019) and Merfield (2019).

CHAPTER 2- REVIEW OF LITERATURE

Regenerative agriculture has gained global recognition as a sustainable approach that focuses on enhancing biodiversity, soil health, and ecosystem resilience. The market for regenerative agriculture offers significant opportunities, driven by the growing demand for sustainable food production systems. As per Precedence Research, the global regenerative agriculture market was valued at USD 975.20 million in 2022 and is expected to expand to around USD 4,290.92 million by 2032, growing at a CAGR of 15.97% between 2023 and 2032.

Figure 1: Global regenerative agriculture market size (2024-2032)



Source: UNFCCC, 2023

Perspectives on regenerative agriculture

Recent academic critiques, such as those by Giller et al. (2021) and McGuire (2018), underscore the gap between farmer claims and scientific validation in regenerative agriculture. Giller et al. (2021) challenge the widespread optimism surrounding no-till farming, questioning its universal benefits and the efficacy of reduced inputs and pesticide use across diverse agricultural settings. In contrast, McGuire (2018) scrutinizes Gabe Brown's assertions about significant increases in soil organic matter through regenerative practices, emphasizing the complexities and variability inherent in natural systems.

The complexity of natural environments complicates definitive statements about the efficacy of agricultural practices across all contexts. Giller et al. (2021) critique the categorical language

often used in discussions of regenerative agriculture, contrasting it with the nuanced approach advocated by McGuire (2018). McGuire highlights discrepancies in terminology, noting the prevalence of "limit tillage" versus "no-tillage" in literature on regenerative agriculture, indicating divergent interpretations and applications within the field.

At the heart of regenerative agriculture lies a holistic perspective that integrates farming within broader ecological systems. This contrasts with reductionist approaches typical of contemporary scientific studies in agriculture, as noted by Jordan (2013). Gordon et al. (2023) further contributes to the discourse by identifying nine distinct discourses within regenerative agriculture, underscoring the need to understand the motivational factors driving farmers towards these practices.

The theories underlying regenerative agriculture

These theories provide a framework for understanding how regenerative agriculture can restore and improve ecosystems, build resilience, and enhance agricultural productivity sustainably. Below are the primary theories:

A. Systems Theory

Core Idea: Regenerative agriculture views the farm as a holistic system where all elements (soil, plants, animals, water, and climate) are interconnected. Changes in one part of the system affect the whole.

Application: Practices like crop diversity, integration of livestock, and natural nutrient cycles are promoted to enhance the overall health of the farm ecosystem.

Key Reference: Capra, F. (1996). The Web of Life: A New Scientific Understanding of Living Systems.

B. Ecological Succession Theory

Core Idea: Farms can mimic natural ecosystems by progressing through stages of ecological succession to create stable, biodiverse environments.

Application: Agroforestry, cover cropping, and reduced tillage are used to mimic natural plant and soil dynamics.

Key Reference: Odum, E. P. (1969). "The strategy of ecosystem development." Science.

C. Soil Health Theory

Core Idea: Soil is a living ecosystem, and its health is foundational to sustainable agriculture. Practices that promote soil organic matter, microbial diversity, and nutrient cycling are central to regenerative agriculture.

Application: No-till farming, organic composting, and minimizing synthetic inputs are emphasized.

Key Reference: Lal, R. (2004). "Soil carbon sequestration impacts on global climate change and food security." Science.

D. Carbon Sequestration Theory

Core Idea: Agricultural practices can act as a carbon sink, removing CO_2 from the atmosphere and storing it in soil and vegetation, mitigating climate change.

Application: Techniques such as rotational grazing, cover cropping, and biochar application are used to enhance carbon capture.

Key Reference: Lehmann, J., & Joseph, S. (2009). Biochar for Environmental Management: Science, Technology, and Implementation.

E. Permaculture Principles

Core Idea: Agriculture should align with natural ecosystems to create self-sustaining environments. Design principles like observing natural patterns, using renewable resources, and waste recycling guide regenerative practices.

Application: Integrating perennial crops, water conservation techniques, and diversified farm systems.

Key Reference: Mollison, B. (1988). Permaculture: A Designer's Manual.

F. Agroecology Theory

Core Idea: Farming systems should be designed based on ecological principles, emphasizing biodiversity, energy efficiency, and resilience.

Application: Regenerative agriculture incorporates agroecological practices such as crop rotations, polycultures, and intercropping.

Key Reference: Altieri, M. A. (1995). Agroecology: The Science of Sustainable Agriculture.

CHAPTER 3- RESEARCH METHODOLOGY

This chapter outlines the methodology employed to investigate the role of water use efficiency (WUE) in promoting regenerative agriculture and enhancing the economy of India. The chapter begins by providing a rationale for the chosen research design, followed by details on data collection, sources, variables, and preparation methods for analysis. The analytical framework utilizes a Simultaneous Equations Model (SEM) to explore the interrelationships between key variables like WUE, crop yields, GDP per capita, employment, and environmental sustainability. Statistical procedures such as correlation analysis, multicollinearity checks, and model fitting are employed to ensure robust results. Additionally, this chapter addresses the issues of validity, reliability, and ethical considerations, followed by a discussion on limitations and their potential impact on the study's findings.

Hypothesis building- null hypothesis (h_0) and alternative hypothesis (h_a)

1. **Hypothesis 1: Harvested Area**
    - **H_0:** Water withdrawals, agricultural land, and yield have no significant effect on the harvested area.
    - **H_a:** Water withdrawals, agricultural land, and yield significantly influence the harvested area.
    - **ϵ_1:** Includes variability in harvested area due to factors such as unrecorded water usage patterns, land management practices, or environmental shocks (e.g., floods, droughts) not included in the model.
2. **Hypothesis 2: GDP per Capita**
    - **H_0:** Harvested area and employment per capita have no significant effect on GDP per capita.
    - **H_a:** Harvested area and employment per capita significantly influence GDP per capita.
    - **ϵ_2:** Represents unexplained variability in GDP per capita arising from factors such as technological advancements, global trade conditions, or policy interventions unrelated to the harvested area or employment.

3. Hypothesis 3: Water Use Efficiency (USD/m^3)

- **H_0:** Water withdrawals and the area equipped for irrigation have no significant effect on water use efficiency.
- **H_a:** Water withdrawals and the area equipped for irrigation significantly influence water use efficiency.
- **ϵ_3:** Accounts for variability in water use efficiency influenced by factors like differences in water quality, inefficiencies in irrigation infrastructure, or unrecorded water-saving practices.

4. Hypothesis 4: Agricultural Land Emissions (Tonne/Ha)

- **H_0:** Harvested area, burning of crop residues, and GDP per capita have no significant effect on agricultural land emissions.
- **H_a:** Harvested area, burning of crop residues, and GDP per capita significantly influence agricultural land emissions.
- **ϵ_4:** Captures emissions variability due to factors such as soil type differences, untracked organic matter decomposition, or variability in farming practices like tillage intensity.

Significance of methodology in achieving research objectives

The methodology section is crucial for achieving clarity, precision, and reliability in this study, ensuring that the research process is transparent and reproducible.

1. **Clarity and Precision**: The methodology clearly outlines the data sources, variables, and analytical techniques used, ensuring transparency and enhancing the credibility of the research.
2. **Reproducibility:** Detailed documentation of the methodology allows for replication by other researchers, confirming the reliability and validity of the results.
3. **Validity and Reliability**: By carefully outlining research design and data collection methods, the study ensures that findings are accurate and consistent. This enhances the overall quality of the research and mitigates biases or errors.
4. **Addressing Complex Interrelationships**: The use of SEM in this study is critical for analysing the complex interrelationships between variables such as water use efficiency, agricultural productivity, soil nutrient balance, and economic growth. This

model captures the dynamic interactions between these variables, providing a comprehensive understanding of their interdependencies.

Specific Variables Used in this Study

1. **Water Use Efficiency (USD/m^3)**: This measures the economic value generated per unit of water used, central to understanding how water is managed and its contribution to agricultural productivity.
2. **Agricultural Production and Yield (Tonnes per Ha)**: Data on crop yields and production levels are analysed to assess the impact of WUE on productivity gains in Indian agriculture.
3. **Agricultural Land (Ha)**: The total land used for agriculture and **irrigated land** are critical indicators of land use efficiency and resource management.
4. **Employment (Per Capita)**: This provides insights into the labor market implications of improvements in agricultural productivity, as well as WUE's influence on rural employment and livelihoods.
5. **Greenhouse Gas Emissions (Tonnes per Ha):** Data on emissions from agricultural land are used to understand the environmental sustainability of agricultural practices, particularly with respect to water use.
6. **Fertilizer Use and Soil Nutrient Balance**: Fertilizer use is evaluated alongside WUE to understand the interaction between water management and nutrient application in improving crop yields.
7. **Energy Use in Agriculture (TJ per Ha)**: Energy consumption in agriculture provides insights into how water extraction and irrigation practices affect sustainability.
8. **Trade Variables (Imports and Exports in Tonnes per Ha)**: Agricultural trade data help assess how improved WUE has impacted India's trade balance, particularly in agricultural commodities.

Justification for using Simultaneous Equation Model in the research

The selection of SEM is critical for this study on water use efficiency (WUE) and its role in agricultural productivity and economic development due to the following key reasons:

1. Complex Interrelationships

- ✓ **Interdependence of Variables**: This study investigates how WUE affects agricultural productivity, soil nutrient balance, and economic development in India.

These relationships are not linear but interrelated; for example, improved WUE increases crop yields, which in turn boosts GDP and employment, creating a cycle of interdependent outcomes.

2. **Handling Endogeneity**
    - ✓ **Simultaneous Determination**: In this study, variables like WUE, GDP, agricultural productivity, and environmental sustainability are simultaneously determined.
3. **Comprehensive Analysis of Multiple Equations**
    - ✓ **Estimation of Multiple Relationships**: By using SEM, the study can simultaneously estimate the effects of WUE on multiple outcomes, such as agricultural productivity, emissions, GDP, and employment.
4. **Policy Implications**
    - ✓ **Simulating Policy Scenarios**: SEM enables the evaluation of potential policy interventions and their effects on multiple sectors. For instance, it can simulate how changes in water management policies could improve WUE, which would influence crop yields, reduce emissions, and contribute to GDP growth.
5. **Complex Systems Modelling**
    - ✓ **Dynamic Feedback Loops:** Agricultural systems are dynamic, with feedback loops where changes in one variable (such as WUE) affect others (like yield and soil nutrient balance). SEM is particularly well-suited for modelling these dynamic, interconnected systems, as it allows for the exploration of cascading effects within the agricultural economy.
6. **Robust Estimation of Parameters**:
    - ✓ Involves the use of statistical techniques that ensure the reliability and accuracy of parameter estimates, even in the presence of outliers, data irregularities, or violations of standard assumptions.
7. **Correcting for Simultaneity Bias**:
    - ✓ By addressing the simultaneity and interdependence of key variables, SEM provides more robust and unbiased estimates compared to single-equation models, which often suffer from simultaneity bias.

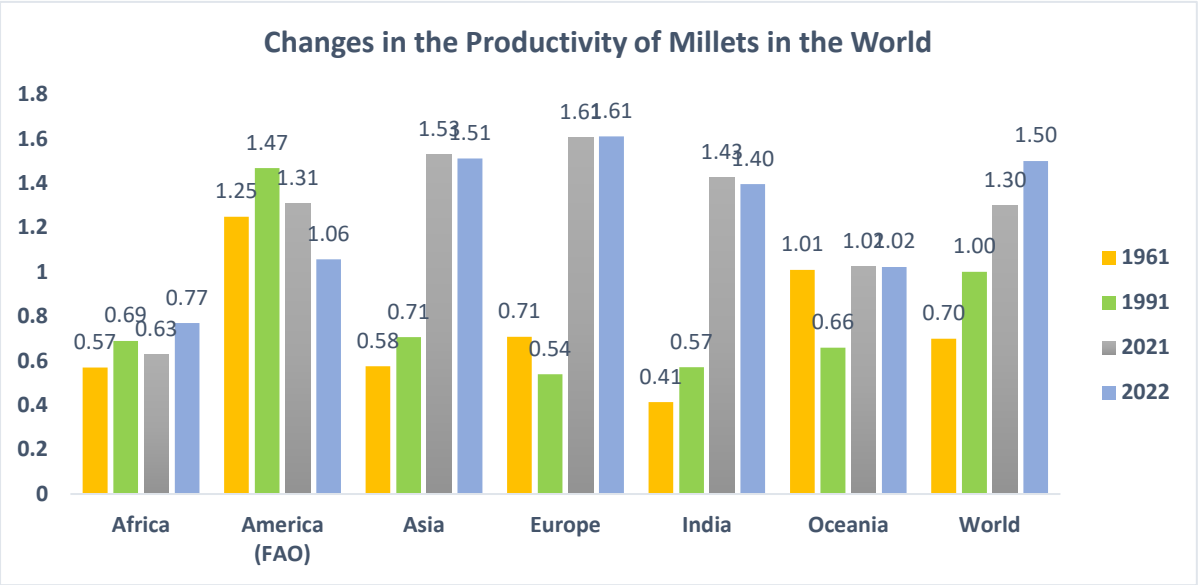
CHAPTER 4- FOOD SECURITY

The world's food and land use systems face numerous interconnected challenges, including the need to feed 10 billion people by 2050, ensure food and nutrition security for all, and maintain humanity within planetary boundaries. Increasing the production of healthy and nutritious food is crucial for achieving food and nutrition security. A meta-analysis conducted by Wageningen University and Research estimates that global food demand will increase by 35% to 56% between 2010 and 2050. Simultaneously, agriculture and food systems are vital engines of economic development and must contribute to global goals of ending poverty and reducing inequality. However, an estimated 828 million people currently face hunger, while obesity rates continue to rise. The economic and political challenges resulting from COVID-19 and Russia's invasion of Ukraine have led to increased costs for basic items such as food and fuel. As of June 2022, the number of people experiencing acute food insecurity has nearly tripled in two years. Climate-related disruptions are also intensifying, with extreme weather events threatening food production and global supply chains. For example, According to World Bank, 2023, Pakistan faced a national food security crisis in 2022 as intense monsoons caused devastating floods, washing away crops and livestock.

Millets: promising crops for the twenty-first century

Panicoids (subfamily: Panicoideae) encompass a diverse group of C4 grasses, including agronomically significant crops such as sorghum and maize, bioenergy feedstocks like sugarcane and miscanthus, nutri-cereals such as millets, and biofuel crops including switchgrass, napier grass, and guinea grass. Millets stand out for their climate-resilient characteristics, including adaptation to various ecological conditions, lower irrigation needs, superior growth and productivity under low nutrient input conditions, reduced reliance on synthetic fertilizers, and minimal susceptibility to environmental stresses (Kole et al., 2015). Nutritionally, millets surpass other major cereals as they are rich in dietary fibers, resistant starches, vitamins, essential amino acids, storage proteins, and other bioactive compounds (Amadou et al., 2013).

Figure 2: Changes in the productivity of millets in the world



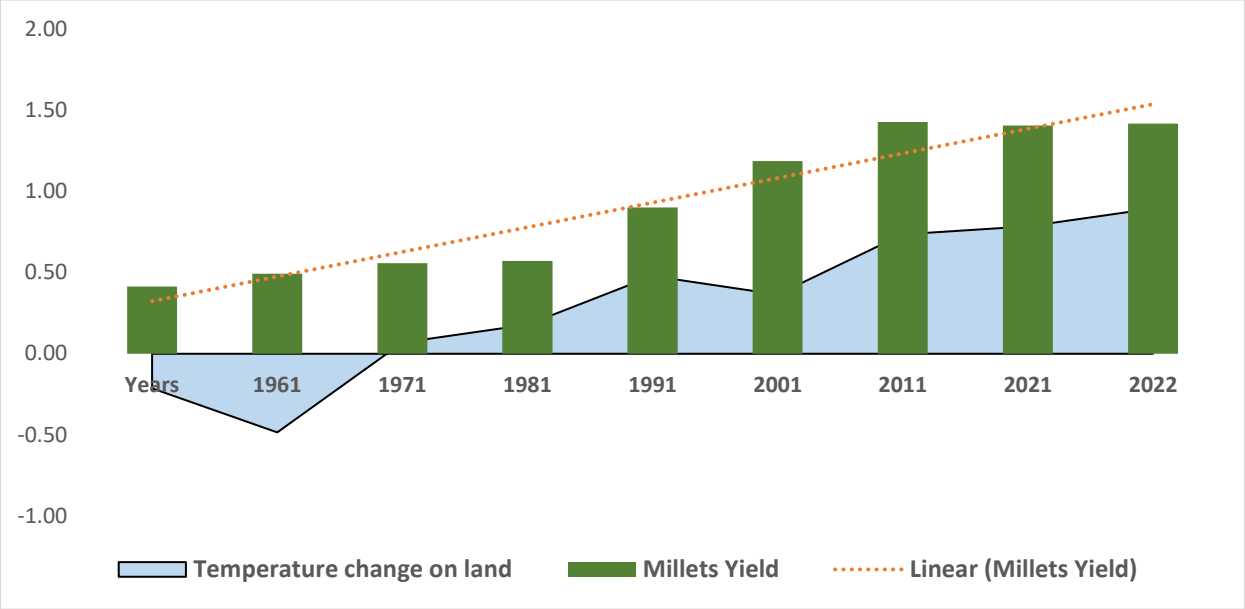
Source of Data: FAO
Graph: Author's calculation

Feeding nearly 10 billion people sustainably by 2050 while safeguarding our environment and enhancing the resilience of agrifood systems is an unprecedented challenge. According to a pre-COVID-19 FAO report, agriculture will need to increase its production of food, fibre, and biofuel by nearly 50% compared to 2012 levels by 2050 to meet the rising demand due to population and income growth. Climate change will have profound impacts on agriculture and food security in the coming decades. By mid-century, higher average temperatures, altered precipitation patterns, rising sea levels, and more frequent and intense extreme weather events are expected to affect crop and livestock production. Focusing on a few high-yielding, input-intensive crops has increased total food production and reduced food insecurity, but it has also resulted in crop concentration. Rice, maize, and wheat provide 60% of the world's food energy intake. Relying on these "big three" crops to feed over 7.5 billion people on a warming planet will make large parts of the global population more susceptible to food insecurity. To prepare for the future, global agriculture systems need to include underutilized crops with high production and consumption potential to make the world food supply more resilient, stable, and nutritious.

Millets are nutrient-dense and climate-resilient crops that are native to G20 countries and could transform global food systems. Each country could promote such crops to ensure greater diversity of food supplies and reduce vulnerability to global shocks. Millets are particularly

well-suited to the dry climatic conditions and multiple cropping systems of India and the semi-arid regions of Asian and African nations. To leverage the potential of millets as a "super-food crop of the future," it is essential to increase awareness on the demand side and develop vibrant value chains on the supply side.

Figure 3: Relationship between millets production and temperature change on land



Data Source: FAOSTAT
Graph: Author's Calculation

Given the complexities, the relationship between temperature changes and millet production can be conceptualized as follows:

- **Moderate Temperature Increases (+1 to +2°C)**:
    - Likely neutral to positive impact on millet production in cooler regions.
    - Possible slight negative impact in already warm regions, depending on the availability of water and other mitigating factors.
- **High Temperature Increases (>+2°C)**:
    - Likely negative impact on millet production due to increased heat stress and soil moisture depletion.

CHAPTER 5- WATER USE EFFICIENCY

The world's current population of 6 billion is projected to reach approximately 8.5 billion by 2030[1], marking a 35% increase and significantly boosting global food demand. Concurrently, water needs from non-agricultural sectors will also rise in both developed and developing nations. With about 40% of the Earth's land under arid and semi-arid conditions (Gamo, 1999), optimizing rainwater use and enhancing crop water use efficiency (WUE) become crucial strategies.

According to FAO (2003), agricultural production in 93 developing countries is expected to rise by 49% in rainfed areas and 81% in irrigated regions from 1998 to 2030. This growth emphasizes the pivotal role of irrigated agriculture, primarily situated in developing nations where the irrigated area doubled between 1962 and 1998. FAO estimates a 23% increase in irrigated area by 2030, yet effective harvested irrigated area, factoring in increased cropping intensity, is projected to grow by 34%. This indicates a need to expand irrigated land to meet rising crop demands with existing water resources.

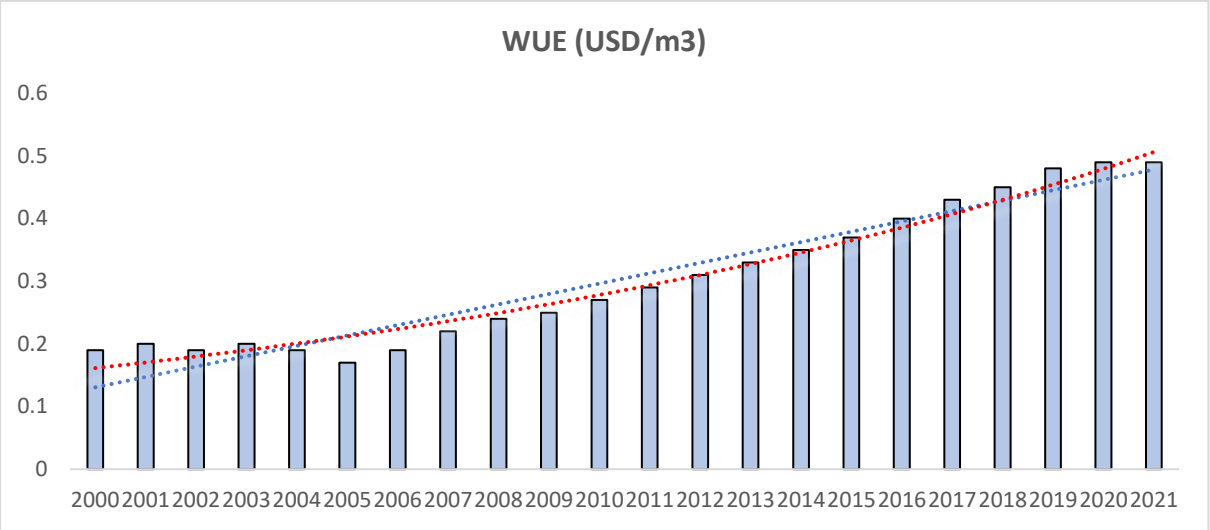
For centuries, humans have been concerned with the efficient use of water in crop production. Efficient water management is crucial for the sustenance of civilizations. Water-use efficiency (WUE) is defined as the amount of aboveground biomass produced per unit area per unit of water evapotranspiration. Typically, this biomass is measured as dry weight rather than fresh weight. The formula for water-use efficiency is:

$$\textbf{Water-use efficiency (WUE)} = \frac{\text{Dry weight production (DW)}}{\text{Evapotranspiration (ET)}}$$

Water-use efficiency can be based on either vegetative growth or reproductive (grain) growth, and it is important to specify which basis is being used. Various units can be used in the numerator and denominator of the equation. Traditionally, measurements were in pounds or tons of dry weight produced per acre-inch of water evapotranspiration (MB Kirkham, 2005).

[1] https://www.un.org/en/global-issues/population

Figure 4: Water use efficiency increase over a period of 2000-2021



Source of Data: FAOSTAT

Graph: Author's Calculation

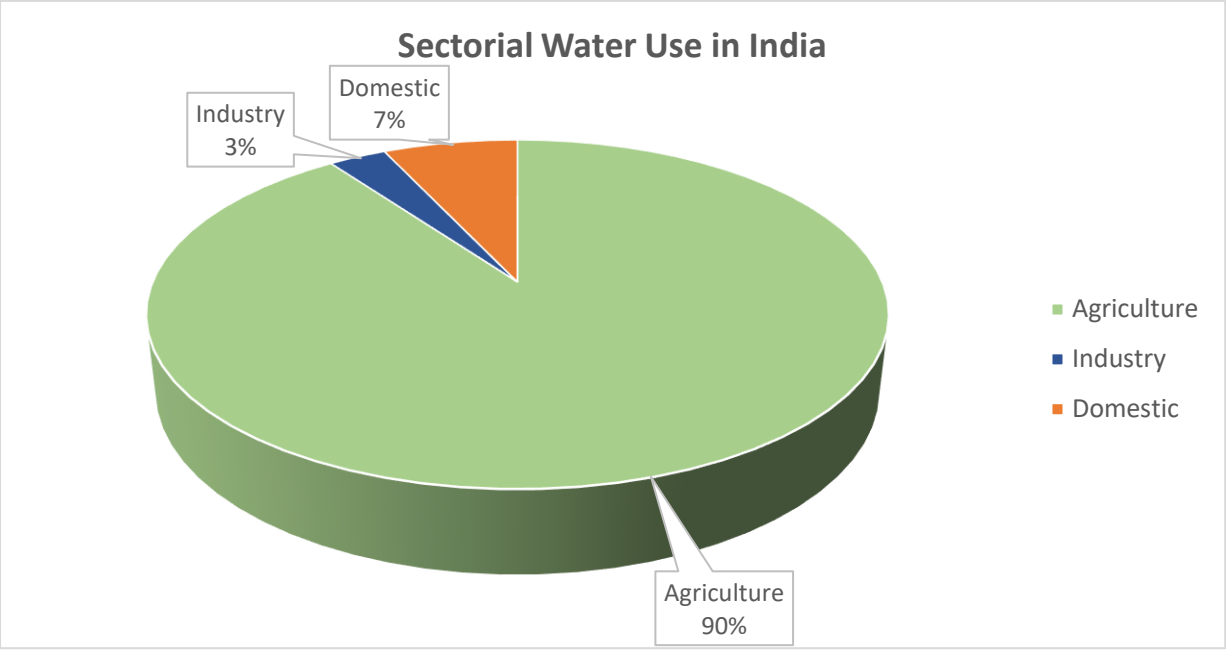
Government initiatives

1. Water Scarcity in Agriculture:
    - India's agriculture faces severe water scarcity, with water use efficiency in conventional irrigation as low as 25-35%.
    - Groundwater extraction rates in India are the highest globally, with 54% of monitored wells classified as overexploited.
2. Importance of Modern Micro Irrigation (MI):
    - MI technologies, including drip and sprinkler systems, offer a significant solution to improve water use efficiency and reduce losses.
    - Drip irrigation is ideal for longer-duration crops like sugarcane and cotton, while sprinkler irrigation suits shorter-duration crops like pulses and millet.
3. Pradhan Mantri Krishi Sinchayee Yojana (PMKSY):
    - Under the "Per Drop More Crop" (PDMC) component, the government promotes water-saving technologies like MI.

- From 2015/16 to 2019/20, approximately Rs. 7800 crores were spent on the PDMC scheme.

4. Challenges and Strategies:
    - Water-intensive crops (e.g., rice, sugarcane) are incentivized by electricity subsidies and low water pricing, contributing to groundwater depletion.
    - Demand-side measures include subsidies for MI, crop diversification incentives, and reforming electricity subsidies to encourage efficient water use.
5. Role of MI Technology:
    - MI systems, developed by companies like Jain Irrigation and Netafim, require higher investments (around Rs. 1.3 lakh/ha).
    - These technologies not only improve water use efficiency but also modernize agriculture, enhance yields, and mitigate the impacts of water scarcity and climate change.
6. Global and National Water Context:
    - Globally, only 1% of water is fresh and suitable for consumption, and over 40% of the world's population faces water scarcity.
    - In India, water availability is at a critical level (1434 cubic meters/person/year), with agriculture accounting for 90% of groundwater extraction.
7. Policy Goals:
    - Expand irrigation coverage under the "Har Khet Ko Pani" initiative.
    - Promote MI adoption to enhance efficiency and reduce water losses from traditional flood irrigation systems.

Figure 6: Sectorial water uses in India



Source: Central Ground Water Board

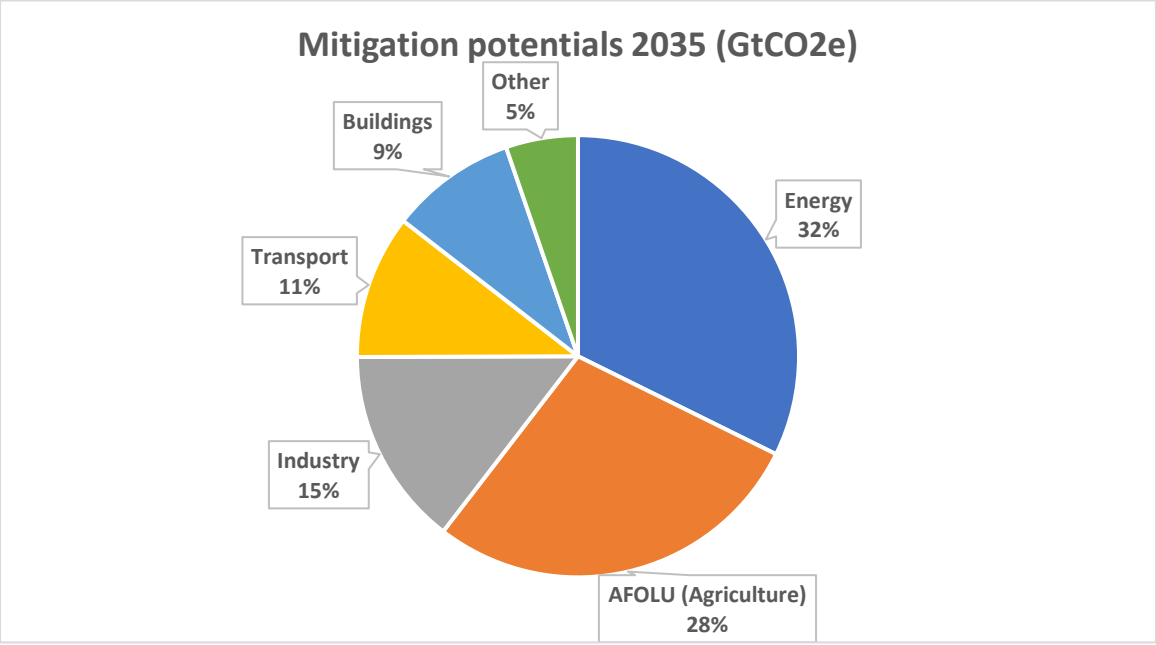
Graph: Author's Calculation

CHAPTER 6- DECARBONIZATION OF AGRICULTURE

Regenerative organic agricultural practices focus on maximizing carbon dioxide absorption through plant growth and minimizing carbon loss once stored in the soil. This process, known as carbon sequestration, involves the net balance between carbon fixed through photosynthesis and carbon released through ecosystem respiration. To effectively achieve on-farm carbon sequestration, explicit management goals are essential, supported by proven regenerative practices that enhance soil carbon levels.

Five principles guide the RA approach: (1) minimize soil disturbance, (2) keep the soil covered year-round, (3) maintain live plants and roots in the soil for as long as possible, (4) incorporate biodiversity, and (5) integrate animals. Advocates and practitioners of RA argue that these methods will prevent soil erosion and depletion, build soil actively, provide appropriate crop nutrients with minimal external inputs, produce healthy, high-yielding crops with few weeds and pests, limit greenhouse gas emissions, increase farmers' financial returns, and improve human health. However, these claims have been widely criticized, with a general consensus that they lack support from rigorous empirical science.

Figure 7: Overview of annual mitigation potentials by 2035 (gtco2e)

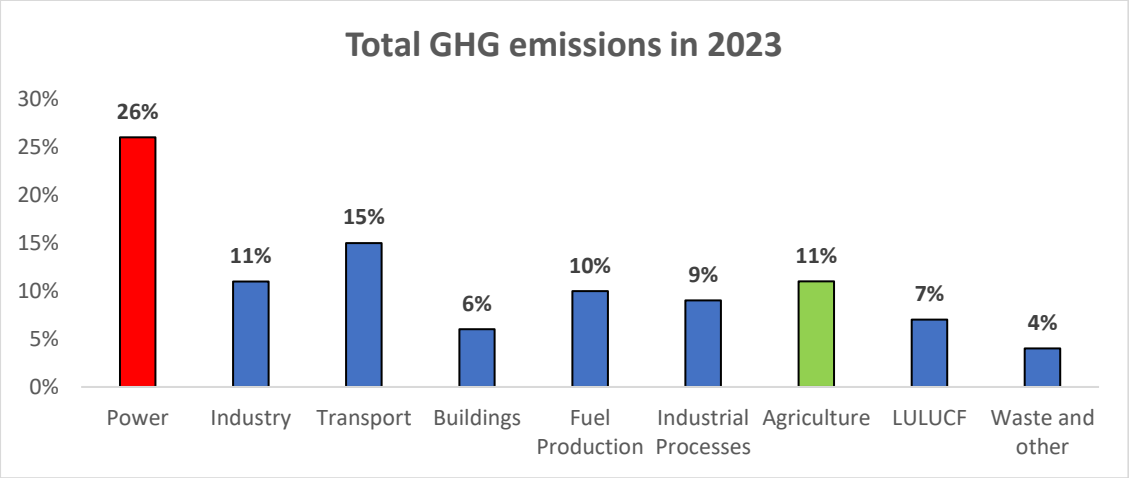


Source: Emissions Gap Report, 2023

GHG emissions from agriculture

To pursue net-zero emissions in agriculture effectively, it is crucial to understand the current contribution of agricultural practices and industries to GHG emissions and their primary sources. Total GHG emissions in 2023 was 57.1GtCO2e in 2023[2].

Figure 8: Total GHG emissions in 2023



Source: Emissions Gap Report 2024

Decarbonization of on-farm energy use

Agriculture is an energy-intensive sector, accounting for approximately 3% of global energy consumption, or about 13 exajoules per year (EJyr−1). This energy is used for various purposes, including producing fertilizers and pesticides, and powering farming activities such as ploughing, harvesting, sowing, threshing, lighting, heating, cooling, and irrigation water pumping. With the projected intensification of agriculture, especially the shift from small-holder to large-scale farming, energy use and reliance on fossil fuels are expected to increase.

CONCLUSION

Decarbonizing on-farm energy use through electrification, renewable energy production, bio-based drop-in fuels, energy efficiency improvements, and sustainable agricultural practices is essential for reducing GHG emissions in agriculture. While these strategies have significant technical potential, their implementation faces challenges related to initial investment costs, energy infrastructure, and regional variations in agricultural practices and resources.

[2] Emissions Gap Report 2024

CHAPTER 7- RESULTS AND DISCUSSION

In this chapter on results and discussion, the data collected from secondary sources regarding water use in regenerative agriculture and its contribution to India's economic development will be analysed. This section will address all the research questions and objectives outlined earlier. A detailed explanation of the research questions, along with the analytical outputs derived from the dataset, will be provided. Additionally, key findings will be discussed and supported by relevant figures and tables.

This section focuses on the following points:

- ✓ Impact of water use efficiency on agricultural productivity in India.
- ✓ Impact on economic activities (mainly GDP per capita and employment) with improvements in water use efficiency.
- ✓ Effects on the environment (mainly carbon emissions and sustainability) with improvements in water use efficiency.

Through statistical analysis, this chapter aims to demonstrate how the variables interact, drawing meaningful conclusions and implications for policy and agricultural practices. The chapter is structured as follows: first, the key results from the model will be examined, followed by a detailed discussion of each finding, supported by appropriate visualizations to enhance the narrative.

Initially, a statistical summary of each variable will be presented alongside basic analyses to illustrate how these variables interact. Preliminary analyses, such as correlation tests, will highlight the relationships between variables, providing a foundation for more complex analyses.

The subsequent section will focus on the statistical model, the Simultaneous Equation Model (SEM), which comprises multiple interdependent equations representing the relationships between variables. Unlike single-equation models, SEM accounts for simultaneity, where dependent variables in one equation may also serve as independent variables in another. This makes SEM particularly valuable for analysing systems with bidirectional and interactive causal relationships.

Finally, the policy implications section will explain the relevance of the results and how they support changes to current policies concerning water use in regenerative agriculture and its role

in India's economic development. All findings will be comprehensively discussed in the concluding discussion section.

TABLE 1:

STATISTICAL SUMMARIES OF THE VARIABLES

Variable	Mean	Standard Deviation	Coefficient of Variation
Agricultural land (Hectare)	179592637	330302.326	0.184
Agriculture area irrigated (Hectare)	65909742.14	4294665.199	6.52
Average of Soil Nutrient Balance (Kilogram Per Hectare)	18.373	2.0776	11.3
Average harvested area (Hectare)	2356685.451	100330.9363	4.26
Burning crop residues (Tonne Per Hectare)	1.9021	0.03616	1.9
Cropland (Hectare)	169253262.5	329971.6795	0.195
Emissions on agricultural land (Tonne Per Hectare)	4.915	0.22367	4.55
Employment (Per Capita)	0.1549	0.04173	26.9
Energy use in agriculture (Terajoules Per Hectare)	0.0014	0.00035	24.6
Agricultural Export (Tonne Per Hectare)	0.0933	0.03175	34
Fallow land (Hectare)	25683363.74	791050.1814	3.08
Forest land (Hectare)	70233156.25	1172593.25	1.67
Gross Domestic Product (Per Capita)	86487.098	40124.28945	46.4
Agricultural Import (Tonne Per Hectare)	0.0585	0.01458	24.9
Land area equipped for irrigation (Hectare)	68970125	2811130.745	4.08
Naturally regenerating forest (Hectare)	57605765.94	673965.8724	1.17

Temperature change on land (Degree Celsius)	0.7103	0.27593	38.9
Water Use Efficiency (USD Per M3)	21.4405	9.60678	44.8
Water Withdrawal (M3 Per Hectare)	3993.2427	129.92168	3.25
Yield (Tonne Per Hectare)	4.8039	0.44087	9.18

Source: Author's calculations

Table 2: Simultaneous equation model using the OLS method

System fit results							
Method: Ordinary Least Square (OLS)							
	N	**DF**	**SSR**	**detRCoV**	**OLS-R2**	**McElroy-R2**	
System	76	58	7.45312	0.000326	0.875781	0.896204	
	N	**DF**	**SSR**	**MSE**	**RMSE**	**R2**	**Adj R2**
eq1	19	14	2.88525	0.240438	0.490345	0.807650	0.759562
eq2	19	15	1.43441	0.110340	0.332174	0.904372	0.889660
eq3	19	15	1.59535	0.122719	0.350313	0.893643	0.877281
eq4	19	14	1.53810	0.129175	0.358015	0.897460	0.871825
The covariance matrix of the residuals							

	eq1	**eq2**	**eq3**	**eq4**
eq1	0.24043780	0.00335509	0.0274040	-0.02626675
eq2	0.00335509	0.11033961	0.0231758	0.00988734
eq3	0.02740395	0.02317579	0.1227192	-0.04533116
eq4	-0.02626675	0.00988734	0.0453312	0.12817481

Model Specification: Key Equations and Insights

Equation 1: Harvested Area

$$Harvested\ Area^{i} = \beta^{0} + \beta^{1} Water\ withdrawl^{i'} + \beta^{2} Agricultural\ land^{i'} + \beta^{3}\ Yield^{i'} + \epsilon 1^{i}$$

- ✓ **Model Fit**: R^2 = **80.76%**
- ✓ **Insights**: Strong explanatory power; weaker relationship between yield and harvested area.

Equation 2: GDP per Capita

$$GDP\ per\ capita^i = \alpha^0 + \alpha^1\ Harvested\ Area^i + \alpha^2\ Employment\ per\ capita^i + \epsilon 2^i$$

- ✓ **Model Fit**: R^2 = **90.43%**
- ✓ **Insights**: Robust model; harvested area and employment strongly influence GDP per capita.

Equation 3: Water Use Efficiency (USD/m³)

$$Water\ Use\ Efficiency^i = \gamma^0 + \gamma^1 Water\ \text{withdrawal}^i + \gamma^2\ Area\ equipped\ for\ irrigation^i + \epsilon 3^i$$

- ✓ **Model Fit**: R^2 = **89.36%**
- ✓ **Insights**: Efficient irrigation is critical for improving water use efficiency.

Equation 4: Agricultural Land Emissions (Tonne/Ha)

$$Agricultural\ land\ emissions^i = \delta^0 + \delta^1\ Harvested\ Area^i + \delta^2$$
$$Burning\ crop\ residues^i + \delta^3\ GDP\ per\ capita^i + \epsilon 4^i$$

- ✓ **Model Fit**: R^2 = **89.75%**
- ✓ **Insights**: GDP per capita is the strongest driver of emissions, followed by crop residue burning.

Discussion of findings

Interpretation and insights:

- **Model Fit:** All equations show a strong fit, with high R^2 values across the board, suggesting that the models explain the majority of the variation in the dependent variables.
- **Statistical Significance:** Key variables like agricultural land, irrigated area, and GDP per capita are statistically significant predictors, especially for equations related to GDP and emissions. However, some variables, like crop residue burning and water withdrawal, show weaker significance.
- **Multicollinearity:** Given the Variance Inflation Factors (VIF) calculated earlier, none of the variables show alarming levels of multicollinearity, as most VIF values remain below the critical threshold (5), except for GDP per capita in some cases.
    - **Consider Adding Interaction Terms:** Since variables like harvested area appear in multiple equations, interactions or non-linear relationships might provide further insights.

The results presented in this chapter emphasize the critical role that **Water Use Efficiency (WUE)** has played in transforming India's agricultural landscape over the study period. The analysis not only highlights how WUE contributes to increased agricultural productivity but also underscores its significant impact on economic growth and environmental sustainability. This section synthesizes the key findings, demonstrating the complex interplay between resource management, agricultural practices, and economic development. It further discusses the broader implications for policy and the future of sustainable agriculture in India.

Key Highlights:

- **Efficiency Without Additional Water Use**: Crop production increased by **72%** between 2005 and 2022, while agricultural water withdrawal remained relatively stable. This reflects the widespread adoption of advanced irrigation systems such as **drip and sprinkler irrigation**, which have enabled farmers to enhance productivity without putting additional pressure on water resources.
- **Synergy Between WUE and Nutrient Management**: Improvements in WUE, alongside optimized nutrient management, particularly the application of nitrogen fertilizers, have driven productivity gains. The balance between water and fertilizer use has been critical in maximizing yields, especially in **water-stressed regions**. However, the analysis shows that an overreliance on nitrogen can lead to diminishing returns and environmental harm.

CHAPTER 8- CONCLUSION AND POLICY RECOMMENDATIONS

Regenerative agriculture presents a transformative opportunity for addressing India's dual challenges of economic development and climate change mitigation. This study highlights how water use efficiency (WUE) and sustainable resource management can serve as critical components of regenerative agriculture, fostering higher agricultural productivity, improving rural livelihoods, and reducing environmental footprints. By enabling farmers to produce more with less water and optimizing inputs such as fertilizers, regenerative practices can drive significant economic growth while contributing to environmental sustainability.

The findings reveal that the adoption of advanced irrigation systems and precision farming techniques has substantially improved agricultural productivity without additional pressure on water resources. The stable levels of water withdrawal and the reduction in GHG emissions further underscore the potential of regenerative agriculture to align economic gains with India's sustainability goals. However, challenges such as overreliance on nitrogen fertilizers and the limited scalability of water-saving technologies highlight the need for a more integrated and balanced approach to resource management.

Scope of the research

1. **Geographical Focus:** The research will focus on India, analysing various regions and states to understand the impact of regenerative agriculture on the nation's GDP and climate change.
2. **Temporal Frame:** The study will cover recent years, ideally from 2000 to the present, to capture the latest trends and developments in regenerative agriculture practices.
3. **Agricultural Practices:** The research will examine specific regenerative agricultural practices such as crop rotation, cover cropping, reduced tillage, and organic farming.
4. **Economic Impact:** Analysis will be conducted on how regenerative agriculture contributes to the agricultural sector's GDP, including factors such as yield improvement, cost savings, and market value of produce.
5. **Environmental Impact:** The study will assess the role of regenerative agriculture in mitigating climate change by examining soil health, carbon sequestration, biodiversity enhancement, and reduction in greenhouse gas emissions.

6. **Policy Analysis:** The research will include an evaluation of existing policies supporting regenerative agriculture in India, identifying gaps and suggesting improvements.
7. **Comparative Analysis:** A comparative analysis will be conducted with conventional agricultural practices to highlight the differences in economic and environmental outcomes.

Limitations of the research

1. **Data Availability:** Limited availability of comprehensive and reliable data on regenerative agriculture practices and their long-term impacts may restrict the depth of the analysis.
2. **Regional Variations:** The diverse climatic and soil conditions across different regions of India may lead to variability in the impact of regenerative agriculture, making it challenging to generalize findings.
3. **Time Frame:** The relatively recent adoption of regenerative practices in India means that long-term impacts may not yet be fully observable, limiting the scope of conclusions regarding sustained economic and environmental benefits.
4. **Economic Valuation:** Quantifying the economic benefits of regenerative agriculture, such as ecosystem services and biodiversity, can be complex and may not be fully captured in traditional economic metrics.
5. **Policy Influence:** Changes in government policies and international trade dynamics can influence the adoption and success of regenerative agriculture, potentially affecting the study's findings.
6. **Technological Adoption:** The adoption of regenerative practices may vary based on farmers' access to technology, education, and resources, potentially skewing results toward more resource-rich regions or communities.
7. **Subjectivity in Stakeholder Opinions:** Perspectives and experiences of stakeholders may be subjective and influenced by personal or regional biases, which could affect the interpretation of qualitative data.
8. **Climate Variability:** The impact of regenerative agriculture on climate change may be influenced by broader climate variability and external environmental factors that are beyond the control of agricultural practices alone.

By acknowledging these limitations, the research aims to provide a balanced and realistic assessment of the potential of regenerative agriculture to contribute to India's GDP and climate change mitigation efforts.

Policy recommendations for promoting regenerative agriculture in india

To capitalize on the potential of regenerative agriculture for fostering economic growth, environmental sustainability, and climate resilience, the Indian government must adopt a comprehensive and multi-dimensional approach. Below are key policy recommendations to promote regenerative agriculture in India:

Incentivizing the adoption of regenerative practices

- **Financial Incentives for Farmers:**
    - Introduce direct subsidies or financial assistance for adopting regenerative techniques such as agroforestry, crop rotation, and cover cropping.
    - Provide interest-free or low-interest loans for investment in equipment, soil health monitoring systems, and advanced irrigation technologies like drip and sprinkler systems.
- **Market-Based Incentives:**
    - Create financial incentives for carbon farming by implementing a carbon credit trading mechanism. Reward farmers for sequestration of carbon and reduction in GHG emissions through regenerative practices.
    - Encourage public-private partnerships to create certification systems for regenerative agriculture, enabling access to premium markets for sustainably produced crops.

LIST OF PUBLICATION AND CONFERENCES

Publications

Sl No	Title of the paper	ISSN No	Journal Name	Date of Publication	Authors
1	Role of Regenerative Agriculture in India's Climate Strategy	0972-6861	The IUP Journal of Applied Economics	Volume 23-No2, Quarterly, Hyderabad, April, 2024	Madhubanti Dutta & Dr Satya Narayan Singh
2	India's Commitment to Hydrogen: Strategic Initiatives and Goals for Climate Change Mitigation	2582-2160	International Journal for Multidisciplinary Research (IJFMR)	Volume 6, Issue 4, July-August 2024	Madhubanti Dutta & Dr Satya Narayan Singh
3	Harnessing Digital Marketing To Mitigate Climate Change: Promoting Sustainable Water Practices	2279-0837,	IOSR Journal Of Humanities And Social Science (IOSR-JHSS)	Volume 29, Issue 7, Series 11 (July, 2024) 28-41	Madhubanti Dutta & Dr Satya Narayan Singh
4	Evaluating the Influence of Water Use Efficiency on India's Economic GDP: A Theoretical Exploration	2456 - 1304	International Journal of Science, Engineering and Management (IJSEM)	Vol 11, Issue 9, September 2024	Madhubanti Dutta & Dr Satya Narayan Singh
5	Book Chapter 3: Advancing the Blue Economy: Integrating Climate Change Mitigation and Carbon Sequestration Strategies	978-81-979350-6-0	Book Name: Maritime Clusters: Port led Industrilizationa and Economic Growth	October, 2024	Madhubanti Dutta & Dr Satya Narayan Singh

6	Book chapter 9: Women Sensitization: A new Chapter for women empowerment in Indian Maritime	978-81-979350-6-0	Book Name: Maritime Clusters: Port led Industrilizationa and Economic Growth	October, 2024	Dr Satya Narayan Singh & Madhubanti Dutta

Conferences Attended

1. **ICSSABE-24 (International Conference on Social Science, Arts, Business, and Education)**
    - **Date:** 11th August 2024
    - **Location:** Delhi
    - **Paper Title:** Evaluating the Influence of Water Use Efficiency on India's Economic GDP: A Theoretical Exploration
    - **Authors:** Madhubanti Dutta, Dr. Satya Narayan Singh
2. **AMANTHRAN - Advances in Management Tourism, Hospitality, and Research Analytics**
    - **Theme:** Business Management and Sustainable Development; Green Marketing, Digital Marketing, and Business Strategy
    - **Organizers:**
        - Guru Nanak Institute of Hotel Management (GNIHM)
        - JIS University
        - In association with Confab
    - **Date:** 20th-21st June 2024 (Thursday and Friday)
    - **Location:** JIS University and GNIHM Campus
    - **Paper Title:** Climate Change Mitigation through Digital Marketing: Strategies in Promoting Sustainable Water Use
    - **Authors:** Madhubanti Dutta, Dr. Satya Narayan Singh